Finite-Element Modeling of Eddy-Current Probe for NDE of Steam Generator Tubes*

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Introduction

The inspection of steam generator tubing is an essential element in ensuring safe and reliable operation of steam generators. Detection of axial cracks in nuclear steam generator tubes continues to be a major challenge. In recent years, the nuclear industry has made significant advancements in developing probes to detect degradation in various regions of steam generator tubing. Although ultrasonic testing can be used to detect such cracks, its inspection speed is very slow. Eddy current testing requires specialized probes and detection is often hampered by the presence of tube deformation and conducting or ferromagnetic deposits.

Eddy-current (EC) nondestructive evaluation (NDE) techniques are currently the primary method for in-service inspection of steam generator tubing [1]. Eddy currents have proved to be useful for detecting, identifying, and characterizing flaws in metal parts [2]. Electromagnetic modelers have had considerable success in applying numerical methods to understanding eddy-current nondestructive testing (NDT) [3,4]. However, interpretation of EC signals is often difficult because of distortion introduced by various internal and external sources. A better understanding of the interaction of the probe with conducting media can lead to improved analysis and interpretation of signals.

Cracks in steam generator tubes can occur due to a variety of mechanisms, such as stress-corrosion cracking, fatigue cracks, or inter-granular attack. They can initiate from the tube ID or OD, and can be axial, circumferential, or branching. They occur most frequently at tubesheet transition, support, and U-bend regions. Present industry standard rotating pancake probes and multi-pancake array probes were initially used in industry. In this model study, both pancake coil and a new transmitter/receiver (T/R) eddy current probe were studied for comparison.

To provide higher spatial resolution and inspection speed, array probes are being evaluated. As part of the effort to evaluate this advanced EC inspection technology, a three-dimensional (3D) finite-element method (FEM) is being used to describe the response of an EC probe to notches in various regions of a tube. With the 3D FEM-based code ELEKTRA [5] (developed by Vector Fields), such calculations could be made to complement experiment data. It could also be used to identify key parameters for improved detection and sizing. The simulation could also aid in developing better data-analysis algorithms.

Description of Work

Finite-element discretization is used to solve the electromagnetic field equations in terms of magnetic vector and electric scalar potentials in conducting media and reduced or total scalar potentials in non-conducting regions. Probe impedance is determined through energy and power

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calculations and is interpreted through changes in the resistance and reactance of the coil. Both signal amplitude and phase from the impedance diagram are used to characterize signal response.

Representative test cases that simulate steady-state AC solutions obtained with a pancake coil were performed. The tube was modeled with inner diameter 19.68 mm (0.775 in.), outer diameter 22.22 mm (0.87 in.), thickness 1.27 mm (0.05 in.), and axial length 60 mm. A notch representing a flaw had an expansion angle 0.5^{o} and a length of 12.7 mm (0.5 in.). The pancake coil had an inner diameter of 0.5 mm (0.02 in.) and outer diameter 2.92 mm (0.115 in.). A measured conductivity of 1000 seimens/mm was used to simulate Alloy600 tube material. Axial notches were simulated with various through-wall depths and lengths. The coil was circumferentially rotated in small steps relative to the notch during tests performed at multiple frequencies. The sludge layer and the roll transition of the tube were simulated. In the case of the sludge layer, the sludge extent was determined by the subtended angle from the center of the tube. For the roll transition, the distance between the coil and the tube was varied.

In all cases, stored energy and power loss were integrated in model simulations to predict the trends of impedance variation (reactance and resistance) of combinations. The resistance is defined from power loss, while the reactance is defined from stored energy of the whole system. As the square root of resistance square and reactance square, the amplitude scaling indicates the magnitude of signal detected by the sensor. The impedance diagram serves as a tool for the correlation between resistance and reactance and also for the amplitude scaling of signal.

The quantities of interest for EC NDE, namely, the change in the coil resistance (R) and reactance (X) for impedance probes can be determined through energy (W) and power (P) calculations [6]:

$$W = \frac{1}{2}\int_V \vec{B} \bullet \vec{H} dV$$

$$P = \int_V \frac{J^2}{\sigma} dV$$

$$A = \sqrt{R^2 + X^2}$$

where B is magnetic flux density, H is magnetic field strength, J is current density, V is volume, and σ is electrical conductivity. Signal amplitude (A) is used to indicate the signal magnitude detected by the probe. The impedance diagram serves as an analytical tool for the correlating resistance and reactance.

Tests Setup

The new approach (B-approach), performed with integral of magnetic flux density on the receiver in a T/R probe, was validated by re-running the test cases of (1) roll transition, (2) 80% and 40% cracks from tube outer-surface, and (3) sludge extent 180 degrees.

To validate the B-approach in cases of roll transitions, twenty tests were simulated with crack 0% under frequencies 200 and 400 kHz, respectively. The new results were compared with results from stored energy-and-power loss integration (E-P approach).

To validate the B-approach in cases of both 40% and 80% cracks from tube outer-surface, thirty-six tests were simulated with axial crack length 12.7 mm under frequencies 200 and 400 kHz, respectively. The new results were compared with results from E-P approach.

To validate the B-approach in cases of sludge extent from outer tube surface, twelve tests were simulated with 80% crack from tube outer-surface (axial crack length 12.7 mm) and with sludge extent 180o under frequencies 200 and 400 kHz, respectively. The new results were also compared with results from E-P approach.

By comparing solutions from both B-approach and E-P approach, modeling of B-approach (X-probe) provides similar shapes of signal response in impedance diagram for tests of roll transition, different crack depths, sludge extent. Scale difference of signal amplitude between E-P approach and B-approach is not a factor for modeling validation. The minor inconsistency of signal response diagram between these two approaches can be caused by meshing. More tests with finer meshing in regions inside the coil are needed for B-approach.

Table 1. Matrix of Calculations

Matrix of Calculations	Bare Tube	Bare Tube with Sludge	Bare Tube with Roll Transition
Notch TW Depth (%)	0%, 100%, 60% (I. and O.)	0% 100%	0% 100%
Coil Position (degrees from notch)	0, 2, 5, 9, 14, 20	0, 2, 5, 9, 14, 20	0
Roll Transition Region (Liftoff Distance: mm)	0.875	0.875	0.875, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0
Sludge Extent	--	4.5, 60, 180^{o}	--
Frequency (kHz)	100/200/300/400	200/400	200/400
Axial Notch Length (mm)	12.7, 30.0	12.7	12.7
Sludge Properties Relative Permeability (no units) Electrical Conductivity [S/mm]	N/A	(10, 100) [1, 100]	N/A

Computation

The analysis modeled the steam generator tube, the notch, the sludge, and the surrounding air in OPERA. To eliminate effects of the mesh coarsement at each point for field evaluation, the signal from a probe coil over a tube with no notch was subtracted from the signal over a tube with a notch.

Vector potential was taken as the variable over the Inconnel tube, notch, and sludge, and the reduced scalar potential was the variable over the air. The active coil was modelled with a solenoid from the library of coil shapes. The ELEKTRA solution used the Lorentz gauge solver. Each solution was then repeated with the notch replaced with the same Inconnel tube as the rest of the tube. The above computations were carried out at phases 0o and 90o.

In this modeling of transmitter/receiver (T/R) probe in steam generator tube, X-probe is composed of one transmitter and one receiver. The receiver is existed in reality, but not existed in model. In post-processing, first, the active coil (transmitter) is erased, then the integration option for fields over the area (from center to mean radius) of receiver is used. The magnetic flux in the receptive coil (receiver assumed, but not existed in the model) is approximated by the integral of the flux density along the axis of the receiver. The integration flux density represents the voltage.

Since flux is in phase with current, and voltage is 90 degree out of phase with flux. The reactance is at phase 0 degree, and resistance is at phase 90 degrees. Again, the amplitude is calculated as the square root of resistance square and reactance square. The impedance diagram is also used as a tool for the correlation between resistance and reactance and also for the amplitude scaling of signal.

Results

In modeling notch response, a series of combinations was set up to compare the effects of key parameters in the EC probe response to notch/sludge geometry (see Table 1). Simulations were performed to model the effect of notch depth and length, sludge, and roll transition at various frequencies for an axial groove.

Preliminary test results have lead to some fundamental conclusions: (a) as expected, signal increases with increasing notch depth and gives stronger response to inner notches than to outer notches (Figure 1), (b) signal amplitude increases with increasing sludge extent, and (c) signal increases with decreasing spacing between the coil and the tube in the roll transition. The results also indicate that for this specific coil, signal amplitude response from short flaws can be characterized approximately by a Gaussian function. For the coil dimensions used here, an array probe should have no less than about 30 pancake coils to detect all flaws around the circumference. These results show the capability of the 3D FEM-based model in predicting the characteristic response of EC probes to flaws in steam generator tubes. Further validation calculations must be conducted on real defects, which often exhibit complex geometry that can differ substantially from the manufactured defects in calibration-standard tubes.

With the test results mentioned in item (1), the new approach was performed with integral of flux density on the receiver in a T/R probe. The comparison was done between the "flux density integration at phase 0 and 90 degrees" and "stored-energy/power loss integration". Trends from the predictions of theses two approaches are similar, but amplitude scaling are different.

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